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Observational constraints on AGB mass loss and its effect on AGB evolution

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Abstract. This review discusses some of the observational constraints on what we know about the mass loss experienced by stars in the Asymptotic Giant Branch (AGB) phase of evolution. Mass loss affects the maximum mass attained by the core of an AGB star and hence its fate as a white dwarf or potentially a supernova. The way mass loss depends on stellar initial parameters and time affects the yield from AGB stars, in terms of elemental abundances and types of dust. The rôle of pulsation, dust formation, chromospheres and other mechanisms which may contribute to mass loss are assessed against observational evidence, and suggestions are made for observations which could force significant new progress in this field in the first decades of the 21st century. A better understanding of AGB mass loss may be gained from a combination with studies of first ascent red giant branch (RGB) stars and red supergiants, through population studies and in different environments.

Key words. Stars: AGB and post-AGB – Stars: carbon – circumstellar matter – Stars: evolution – Stars: mass-loss – Stars: winds, outflows

1. Evidence for mass loss on the AGB

Shklovsky (1956) proposed an origin of the expanding Planetary Nebulae (PNe) at the Asymptotic Giant Branch (AGB), the last phase of evolution of stars with initial masses between $M_{\rm init} \sim 0.8$ and 8 $M_\odot$.

Deutsch (1956) presented the detection of optical absorption lines in front of the warm companion to the M5 III giant in the α Herculi binary. He interpreted this as a wind emanating from the cool giant, which loses mass at an estimated rate $\dot{M} > 3 \times 10^{-8}$ $M_\odot$ yr^{-1}.

Gehrz & Woolf (1971) detected infrared (IR) emission from warm — hence circumstellar — dust around cool giant stars, including α Her for which they estimated $\dot{M} \sim 9 \times 10^{-8}$ $M_\odot$ yr^{-1}, consistent with Deutsch' analysis. For strongly pulsating (Mira) red giants they derived much higher mass-loss rates, $\dot{M} \sim 2 \times 10^{-6}$ $M_\odot$ yr^{-1}. They suggested that the winds of Miras may in fact be driven through radiation pressure on these dust grains.

Hydroxyl (OH) maser emission is observed at radio wavelengths from the most dust-enshrouded M-type stars (OH/IR stars). The wind velocity can be measured from the line profiles, confirming the dust-driven wind scenario (Elitzur, Goldreich, & Scoville 1976; Richards & Yates 1998). Rotational lines of the abundant carbon monoxide molecule (CO) are present in emission at (sub)mm wavelengths in all dusty winds including those of carbon stars (Knapp & Morris 1985). These are thermally excited transitions and thus more reliable for mass-loss rate measurements.

2. Global constraints on mass loss

2.1. Initial-final mass (IFM) relation

AGB stars are believed to end their lives as a white dwarf, their electron-degenerate carbon-oxygen core. These can not be more massive than $\sim$ 1.4 $M_\odot$, or they would implode (Chandrasekhar 1931). If this happens whilst still inside the AGB star, a supernova type 1.5 would result (Iben & Renzini 1983). This has never been seen to occur. Hence AGB stars with masses $M_{\rm init} > 1.4$ $M_\odot$ *must* shed their mantle to truncate any further growth of their core. For the most massive AGB stars this means several solar masses must be lost, and quickly enough.

The white dwarf mass distribution peaks at $\sim$ 0.6 $M_\odot$, both in the Small Magellanic Cloud, SMC (Villaver, Stanghellini, & Shaw 2004), in the Large Magellanic Cloud, LMC (Villaver, Stanghellini, & Shaw 2007), and in the Milky Way. The initial-final mass (IMF) relation seems to vary little between galactic open clusters of different metallicity (Williams 2007). This suggests that low-mass AGB stars must also lose mass, and that the total mass lost on the AGB depends little, if any, on the metal content. Differences within 0.1 $M_\odot$ can easily be explained by differences in star formation histories or observational bias.

Does this also mean that the mass-loss *rate* depends little on metallicity? No. AGB stars reach mass-loss rates two-three orders of magnitude higher than the core growth rate (van Loon et al. 1999). This causes the core to grow very little during the phase of heaviest mass loss (this is not the case for red supergiants, RSGs, which seem unable to escape a supernova ending). If the mass-loss rates were lower by an order of magnitude, AGB stars would live longer, but not enough for the core to grow a lot. Only when the mass-loss rate drops to within a few times the core growth rate will the core grow significantly. This would require the mass-loss rate not to exceed $\sim 10^{-7} - 10^{-6}$ $M_\odot$ yr^{-1} for any significant amount of time (depending on core mass), unlike what is observed in the Magellanic Clouds (van Loon et al. 1999) and solar neighbourhood (Jura & Kleinmann 1989).

2.2. Population studies and yields

For all but the most extreme initial mass functions, any stellar population will eventually produce AGB stars. Population studies of the luminosity functions of oxygen-rich and carbon AGB stars (Groenewegen & de Jong 1993) could, in principle, constrain AGB mass-loss, but these studies usually adopt a certain mass-loss formalism, concentrating instead on calibrating aspects of internal processes such as the dredge-up efficiency. But for example an apparent lack of PN precursors and luminous carbon stars (Wood, Bessell, & Fox 1983; Reid, Tinney, & Mould 1990) was alleviated after IR surveys revealed a large population of optically invisible stars in a phase of intense mass loss and dust production (Wood et al. 1992; van Loon et al. 1997, 2006).

The AGB stars will lose mass enriched in products of nucleosynthesis, and dust. These products are encountered in the interstellar medium (ISM), next generations of stars or even in our Solar System, and can thus shed light on AGB mass-loss.

Ferrarotti & Gail (2006) showed that different mass-loss formalisms result in different timings during AGB evolution of the Mira phase and subsequent OH/IR phase, and that dust production depends on initial metallicity. They predicted that at solar metallicity, $Z_\odot$, a 2 $M_\odot$ star produces little carbonaceous dust, as it becomes a carbon star only very late, whilst stars of low initial metallicity, $Z_{\rm init} = \frac{1}{20}$ $Z_\odot$, produce solely carbonaceous dust across the entire AGB mass range.

Zinner et al. (2006) analysed meteoritic evidence for the origin of dust. They studied the silicon carbide grains due to AGB carbon stars, most of which appear to come from metal-rich stars. They require a rather low mass-loss efficiency, Reimers' Law (Reimers 1975) with efficiency $\eta = 0.1$, to explain the observed isotopic ratios. Stronger mass loss results in fewer thermal pulses on the AGB, affecting the chemical yields. Karakas et al. (2006) found that adopting Reimers' Law instead of the Vassiliadis & Wood (1993) prescription causes $\sim$ 75% drop in yields for elements such as magnesium, aluminium, and silicon.

3. What is the rate of AGB mass-loss?

3.1. Measured mass-loss rates

The most common methods to derive mass-loss rates from AGB stars are based on the IR emission from the circumstellar dust, or CO emission from the molecular envelope; they were reviewed recently in van Loon (2007) and Schöier (2007), respectively.

A compilation of mass-loss rates from Galactic M-type, carbon and the intermediate S-type (carbon:oxygen ratio nearly unity) AGB stars was published recently by Guandalini et al. (2006) and Busso et al. (2007). The carbon stars were found to be the more obscured stars in general, but this is in part due to the higher opacity of carbonaceous dust. They reach $\dot{M} \sim 10^{-5}$ M$_\odot$ yr^{-1} (Jura & Kleinmann 1990), similar to OH/IR stars (Olnon et al. 1984) but much higher than the less evolved optically bright Miras (Jura & Kleinmann 1992). The S-type stars were initially found to have comparatively low mass-loss rates, $\dot{M} \sim 10^{-7}$ M$_\odot$ yr^{-1} and a dust:gas mass ratio, ψ, a few times lower than the typical $\psi \sim 0.005$ in M-type and carbon stars (Jura 1988). But Ramstedt et al. (2006) find a similar median $\dot{M} \sim 2\times10^{-7}$ M$_\odot$ yr^{-1} for S-type, M-type and carbon AGB stars on the basis of CO emission. It is therefore not clear whether the mass-loss rate depends critically on the carbon:oxygen ratio.

Complete samples of AGB stars may be obtained in the Magellanic Clouds, and their mass-loss rates appear to reach similar values as in the Milky Way after scaling the wind speed and dust:gas ratio with metallicity and luminosity (van Loon 2000, 2006). This was confirmed recently in other nearby dwarf galaxies (Jackson et al. 2007a,b; Lagadec et al. 2007b). Groenewegen et al. (2007), using *Spitzer Space Telescope* spectra, also obtained similar mass-loss rates for SMC and LMC carbon stars, but using Galactic values for the wind speed and dust:gas ratio; they also find an identical correlation with period of pulsation as in the Milky Way. It must be noted that the sample is heavily restricted to carbon stars only, in a narrow mass range around ~ 1.5 M$_\odot$.

Blommaert et al. (2006) modelled the spectral energy distributions of M-type AGB stars in the Galactic Bulge, deriving low mass-loss rates, $\dot{M} \sim 10^{-8} - 10^{-7}$ M$_\odot$ yr^{-1}. These are low-mass stars, $M_{\rm init} \sim 1$ M$_\odot$, and it must be realised that in smaller stellar systems it is more difficult to capture the brief phase of intense mass-loss. This is in particularly true for star clusters (Jura 1987; van Loon, Marshall, & Zijlstra 2005).

The slow winds and ability to detect cold dust and gas allow variations in the mass-loss rate to be traced over as much as 10^4 yr, about a thermal-pulse interval. Jura (1986) and Groenewegen et al. (2007) found $>$ 10% of carbon stars to have varied noticeably in mass-loss rate over the past $10^2 - 10^3$ yr. Decin et al. (2007) presented a detailed account of mass-loss variations in an OH/IR star, WX Piscis.

3.2. One formula fits all?

An early empirical formula for the mass-loss rates of red giants, Reimers' Law (Reimers 1975) does not reproduce the very high rates found in OH/IR stars and their carbon star equivalents. In a heroic attempt to describe the mass loss across the entire Hertzsprung-Russell diagram with one $\dot{M}(L, T_{\rm eff})$ formula, de Jager, Nieuwenhuijzen, & van der Hucht (1988) failed on the AGB.

Judge & Stencel (1991) fitted $\dot{M} \propto g^{-1.5}$, where g is the gravity, to within an order of magnitude of data ranging from first-ascent red giant branch (RGB) stars with $\dot{M} \sim 10^{-9}$ M$_\odot$ yr^{-1}, to AGB stars with $\dot{M} > 10^{-5}$ M$_\odot$ yr^{-1}.

Vassiliadis & Wood (1993) fit $\log \dot{M} \propto P$ to CO mass-loss rates and pulsation periods, P, with no difference between M-type and carbon AGB stars. Their sample is dominated by stars in a narrow range of mass, $\sim 1-2$ M$_\odot$. The relation is shifted to longer periods at higher mass; this introduces orders of magnitude difference in mass-loss rate at a given pulsation period for stars that differ in mass by only a factor two or three. At approximately $P > 600$ days, the mass-loss rates of OH/IR stars derived from the 60 μm flux density are seen to saturate around a value $\dot{M} \sim 10^{-4}$ M$_\odot$ yr^{-1}, just a little above the single-scattering limit (Jura 1984).

A formula of the form $\dot{M}(L, T_{\rm eff})$ was derived by van Loon et al. (2005) for oxygen-rich massive AGB stars and red supergiants (RSGs) in the LMC. It was found to also describe Galactic stars, except some of the warmer or weaker pulsating ones. The formula is similar to results from hydrodynamical computations (Wachter et al. 2002) for carbon stars, which do exhibit a similar behaviour in the LMC data: the mass-loss rate scales roughly in proportion to luminosity, which provides the radiation pressure, and strongly with lower temperature, which allows dust formation.

4. How is AGB mass-loss driven?

4.1. The rôle of dust

In the wind of a luminous, cool star, dust is always observed. That it also drives the wind is confirmed with interferometric maser observations of nearby OH/IR stars (Richards & Yates 1998) and the wind speeds in OH/IR stars (Marshall et al. 2004) and optical depths in both M-type AGB and carbon AGB stars (van Loon 2000) in the Magellanic Clouds and Milky Way. Habing, Tignon, & Tielens (1994) predicted a slightly steeper luminosity dependence of the wind speed (exponent 0.3 instead of $\frac{1}{4}$), which would indeed fit better the data in Marshall et al. (2004).

The Eddington luminosity required to drive a wind via dust is reached near the tip of the RGB for carbonaceous dust, but only higher up the AGB for silicates because they are more transparent (Ferrarotti & Gail 2006). The exact threshold in terms of the coupling between the dust and gas fluids is uncertain: Netzer & Elitzur (1993) estimated $\dot{M} > 10^{-7}$ $M_\odot$ yr^{-1} but Gail & Sedlmayr (1987b) $> 10^{-6}$ $M_\odot$ yr^{-1}. To produce a dust-driven wind from a pulsating M-type star, Woitke (2006) required iron to provide opacity; this could help explain the metallicity dependence of AGB mass-loss (van Loon 2006).

Alternatively, Höfner & Andersen (2007) suggested that an M-type star may form some carbonaceous dust, which could supply the opacity. This scenario could help explain that the smooth transition from slow winds and low mass-loss rates to faster denser winds measured in CO is undistinguishable between M-type, S-type and carbon AGB stars (Knapp et al. 1998).

There is a great deal uncertainty about the details of the dust formation process (Jura & Morris 1985; Gail & Sedlmayr 1987, 1999; Ferrarotti & Gail 2006), but meteoritic evidence shows that grains condense around nucleation seeds based on titanium (Bernatowicz et al. 1991), which in oxygenous environments are coated by aluminium-oxides and then by silicates (Vollmer et al. 2006). Observations in 47 Tucanae show indeed that the brightest, AGB star has formed silicate dust (van Loon et al. 2006b), but that fainter stars generally show features from aluminium-oxygen bonds (Lebzelter et al. 2006).

Although carbon AGB stars produce their own main dust condensate, carbon, and van Loon, Zijlstra, & Groenewegen (1999) (and Matsuura et al. 2005; Sloan et al. 2006; Zijlstra et al. 2006; Lagadec et al. 2007a) show that metal-poor carbon stars have very strong molecular bands because of a higher availability of carbon, there is no evidence suggesting that metal-poor carbon stars have a higher dust content. The molecular mass-loss rates are consistent with the dust mass-loss rates (Matsuura et al. 2006) for $\psi \propto Z_{\rm init}$, which was found initially from analysis of dust optical depths (van Loon 2000). This is further supported by a comparison of the available amount of silicon with the strength of the silicon-carbide features in carbon stars in the Fornax dwarf galaxy (Matsuura et al. 2007), and a low dust content seen in magellanic carbon PNe (Stanghellini et al. 2007).

Titanium (or zirconium or silicon) is pivotal as a seed for carbonaceous dust to nucleate onto, so the number density of grains is $n_{\rm grains} \propto Z_{\rm init}$. Grain growth is determined by $n_{\rm seeds} \times n_{\rm condensates}$. If more carbon is available, larger molecules form such as acetylene (van Loon et al. 2006; Matsuura et al. 2006) or even macromolecules. The *number density* of carbonaceous molecules may thus not be that dissimilar between carbon stars of different $Z_{\rm init}$, and the dust:gas ratio may depend mostly on $n_{\rm seeds}$ and thus $\psi \propto Z_{\rm init}$.

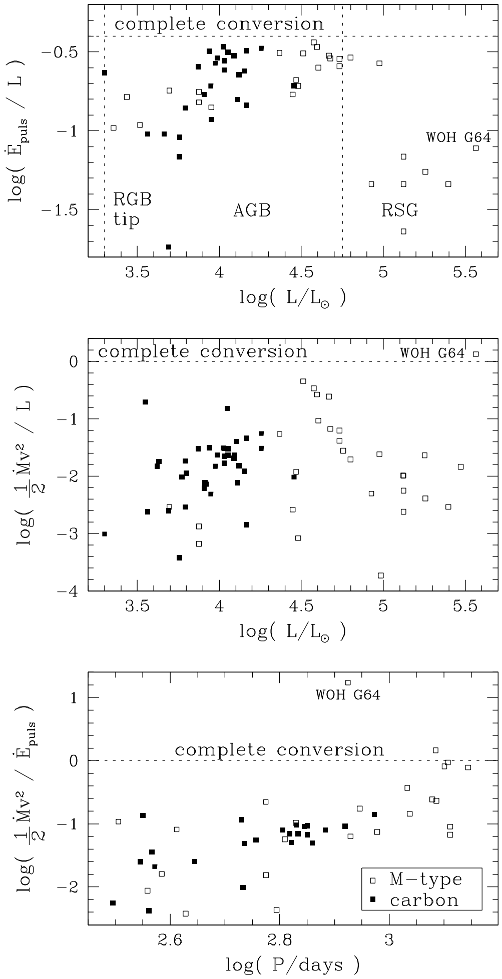

Fig. 1. The mean energy rate involved in pulsational expansion as a fraction of the luminosity, versus luminosity (top), and the kinetic energy in the ejecta compared to luminosity, versus luminosity (centre) and compared to the pulsational energy rate, versus pulsation period (bottom). See text for details.

4.2. The rôle of pulsation

Paczyński & Ziółkowski (1968) established a link between Miras and PN ejection, and thick dust shells are always seen in conjunction with strong pulsation in the fundamental mode (Jura 1986). Pulsation is believed to be the initial stage in launching a wind, with dust formation providing the final stage in driving it away (Bowen & Willson 1991; Wachter et al. 2002).

To quantify the potential of pulsation to drive a wind, van Loon (2002) introduced the mean energy rate involved in pulsation, taking the K-band amplitude as a proxy for a sinusoidal bolometric light modulation (cf. van Loon et al. 2006). Using data in the LMC (Whitelock et al. 2003; van Loon et al. 1999, 2005), the pulsation of AGB stars appears to saturate just below the maximum attainable conversion of photons into mantle expansion (Fig. 1, top), whilst RSGs clearly pulsate less strongly. Nonetheless, the efficiency with which mechanical energy is transferred from pulsation to a wind is a smooth function of pulsation period and, as before, indistinguishable for M-type and carbon AGB stars (Fig. 1, bottom), remaining significantly less than 100% for all but the most extreme OH/IR stars. In general, the radiation field is found to contain 10-1000 times more energy than required to support the wind (Fig. 1, centre), independent of stellar luminosity, suggesting the mass loss is determined more critically by the pulsation than by the radiation.

There exists a transition regime between stars where radial pulsation is unimportant, and Miras. These semi-regular variables were found to have low mass-loss rates as derived from IR emission, $\dot{M} \sim 10^{-7}$ M$_\odot$ yr^{-1} or less (Knapp et al. 1998). On the other hand, CO measurements of semi-regulars compared to Miras suggested that mass-loss rates are unaffected by the pulsation mode (Kahane & Jura 1994) — perhaps semi-regulars are simply less dusty. At pulsation periods $P > 200$ days the mass-loss rates are higher and increase with increasing period (Knapp et al. 1998). This is partially due to more luminous (bigger) stars having longer periods as well as more radiative momentum to drive the wind. Similarly, the pulsation period is longer for cooler (bigger) stars which form dust more easily as it can form closer to the star where the density is higher. But some stars with “short” periods exist which are cool (such as EP Aquarii, R Leonis, or W Hydrae) but have little dust. The short pulsation cycle times and smaller amplitudes of semi-regular variables pulsating in an overtone may leave less time for dust to form, in a weaker pulsation shock.

Some semi-regulars (e.g., EP Aqr) show both a fast and a slow component in their wind (Knapp et al. 1998). This could indicate some instability in the wind driving mechanism inherent to the pulsational transition regime.

4.3. The rôle of chromospheres

The chromospherically active, early M-type RSG Betelgeuse is a famous example of a star which is relatively warm, has little dust and does not pulsate very strongly, but which nevertheless has $\dot{M} \sim 10^{-5}$ M$_\odot$ yr^{-1} (van Loon et al. 2005). Could mass loss from AGB stars be driven by a chromosphere too?

Judge & Stencel (1991) show that chromospheres and dust-driven winds carry a similar energy flux as fraction of the bolometric luminosity, $\sim 10^{-6} - 10^{-4}$, with little evidence for anything other than a seamless transition. Hence, they suggested that it does not really matter what the mechanism for driving the wind is, as plenty of energy is available for a host of mechanisms to operate, one of which may (but need not) dominate. They suggest that the ability to lose mass at a given rate is set principally by the depth of the gravitational potential well, i.e. the surface gravity.

McDonald & van Loon (2007) analysed the optical line profiles of stars above and below the RGB-tip in globular clusters; some, but not all, of these stars have dust. Pulsation shocks were most clearly visible in the Hα line profiles of the strong pulsators, which tend to be the most luminous stars and likely on the AGB. The mass-loss rates estimated from the absorption line profiles agreed with those derived from the IR emission (Origlia et al. 2002), as well as with the heuristic model for a circumstellar origin of the Hα emission wings (Cohen 1976), but they were an order of magnitude higher than Reimers' Law predicts.

Schröder & Cuntz (2005) modified Reimers' Law with a heuristic argument for the calibration in terms of stellar temperature. This would cause metal-poor (warmer) stars to lose mass at a higher rate. This could cause bluer horizontal branches. On the other hand, van Loon et al. (2007) suggest metal-poor stars in ω Centauri lose slightly less mass on the RGB and thus become more often post-AGB stars than their metal-richer siblings. This would also explain the rare presence of a PN in the very metal-poor globular cluster, M 15.

5. Mass loss and AGB evolution

Mass loss truncates the growth of the core and hence AGB evolution and the number of thermal pulses. Vassiliadis & Wood (1993) show that mass loss according to their formula kicks in more suddenly and later in the AGB evolution than Reimers' Law, as it depends more extremely on L and $T_{\rm eff}$ — or rather radius, as they parameterised it as $\dot{M}(P)$. Mass loss also reduces the mantle mass and density and thus the effect of 3$^{\rm rd}$ dredge-up. This could cause Hot Bottom Burning to stop, allowing for a final thermal pulse to convert a massive oxygen-rich AGB star into a carbon star (van Loon et al. 1998; Frost et al. 1998). On the other hand, I have argued previously that mass loss will need to become very much less efficient to affect the IFM relation.

Super-AGB stars, which ignite carbon, are not well represented or recognised in current samples, which might be understood if they do not become as cool and hence dust-enshrouded as slightly less massive shell-burning AGB stars or slightly more massive core-helium burning supergiants. If this means they do not lose mass very fast then this could prolong their life and thus facilitate an electron-capture supernova end, rather than leaving an oxygen-neon white dwarf (cf. Siess 2007).

Mass loss causes an AGB star to expand, which may facilitate mass loss. The pulsation period could then reach the thermal timescale, in which case the star will adjust itself continuously to the new configuration (van Loon 2002). It is unclear what effects this will cause.

6. Critical measurements to make

Measurements which can (soon) be made, and which would greatly advance understanding of AGB mass-loss, include the following:

1 Measure the IFM relation at < 0.1 Z$_\odot$;
2 Measure the wind speed and dust:gas ratio in metal-poor carbon stars;

3 Measure chromospherically-driven winds;
4 Correlate mass-loss rates with gravities;
5 Spectro-interferometric monitoring of the pulsating atmosphere and dust formation region, (near-)contemporaneous with interferometric maser observations;
6 Reconstruct the mass-loss history through IR or (sub)mm observations of envelopes;
7 Population synthesis of Local Group AGB star populations to *derive* a prescription for mass-loss rate, dust production and yields as function of stellar parameters and time.

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